Composite Higgs from Higher Representations

Deog Ki Hong*

Department of Physics, Pusan National University, Pusan 609-735, Korea

Stephen D.H. Hsu†

Department of Physics, University of Oregon, Eugene OR 97403-5203

Francesco Sannino‡

NORDITA, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

We investigate new models of dynamical electroweak symmetry breaking resulting from the condensation of fermions in higher representations of the technicolor group. These models lie close to the conformal window, and are free from the flavor-changing neutral current problem despite small numbers of flavors and colors. Their contribution to the **S** parameter is small and not excluded by precision data. The Higgs itself can be light and narrow.

INTRODUCTION

The simplest QCD inspired models of dynamical electroweak symmetry breaking face a number of challenges: precision electroweak constraints, suppression of flavor changing neutral currents, generating the observed quark masses, and producing large enough masses for any uneaten Goldstone bosons [1]. If the strong dynamics at the electroweak scale is almost conformal [2, 3, 4] it is easier to suppress flavor changing neutral currents on one hand, and to reduce contributions to the **S** parameter on the other [5, 6, 7, 8]. We define near-conformal behavior by the smallness of the β-function. When the β-function is small the gauge coupling constant "walks" rather than runs over a large range of energy.

In early models, a large number of fermions were needed to tune the theory close to the conformal window [1]. Recently it was shown that adding matter in two-index representations (either symmetric or antisymmetric) of the technicolor group allows one to reach the conformal window with only a small number of flavors and colors [10]. Indeed, N_{Tf} is constrained to be $2 \leq N_{Tf} \lesssim 4$ for any number of colors N. The resulting contribution to **S** is reduced significantly, even in perturbation theory. Near the conformal window, **S** is probably reduced even more by non-perturbative dynamics, as we discuss below. The models we consider are no more than 1-2 standard deviations from the central value of precision data, according to our best estimates. (Our models should not be confused with earlier work in which matter in higher representations of QCD ("quixes") were used to break electroweak symmetry [9].)

Other positive features of our models are as follows (see below for details). (1) The near-conformal behavior of the theory allows the scale of fermion mass generation to be large, naturally suppressing flavor changing neutral currents. (2) The mass of the composite Higgs m_H may be much lighter than expected in models of dynamical symmetry breaking. Using a correspondence with supersymmetric Yang-Mills theory which is exact at large N and $N_{Tf} = 1$, we obtain a rough estimate of $m_H \sim 200 - 500$ GeV. (Note that in this paper we only use supersymmetry as an analysis tool to obtain Higgs mass estimates through a large-N correspondence - the models themselves are not supersymmetric.) (3) In our favored models, which have $N_{Tf} = 2$, all Goldstone bosons resulting from symmetry breaking are eaten by the electroweak gauge bosons. The favorable features of $N_{Tf} = 2$ might hint at the origin of the $SU_L(2)$ gauge symmetry.

This paper is organized as follows. First we specify several models and give a table of some of their important properties. Next we discuss, in turn, fermion mass generation, the **S** parameter and the Higgs mass and particle spectrum.

MODELS

The simplest technicolor model TC has N_{Tf} Dirac fermions in the fundamental representation of $SU(N)$. These models, when extended to accommodate the fermion masses through ETC interactions, suffer from large flavor changing neutral currents. This problem is alleviated, at least to the extent of accounting for masses up to that of the b quark, if the number of flavors is sufficiently large such that the theory is near conformal. This is estimated to happen for $N_{Tf} \sim 4N$ [2], which implies a large contribution to the **S** parameter (at least in perturbative estimates). We denote a generic, not near-conformal, technicolor type model, with fermions in the fundamental representation, as $TC(N, N_{Tf})$. If it is near-conformal we use $WTC(N, N_{Tf})$.

Near the conformal window [6, 7] the **S** parameter is reduced due to nonperturbative corrections, but might still be too large if the model has a large particle content. In addition, such models may have a large number of unwanted pseudo Nambu-Goldstone bosons. By choosing

a higher dimension representation for the fermions one can overcome these problems.

The simplest theories investigated in [10] have fermions in the two-index symmetric (S-type) or antisymmetric (A-type) representation. In Table I we present the generic S-type theory. At infinite N and with one

	$SU(N)$	$SU_L(N_{Tf})$	$SU_R(N_{Tf})$	$U_V(1)$	$U_A(1)$
$q_{\{ij\}}$	⊞	□	1	1	1
$\widetilde{q}^{\{ij\}}$	⊞	1	□̄	−1	1
G_μ	Adj	0	0	0	0

TABLE I: The fermion sector in the case of the symmetric representation. Here q and $\widetilde{q}$ are Weyl fermions.

Dirac flavor, the S and A type theories become non-pertubatively equivalent to super Yang-Mills [11]. This property was used in making predictions for QCD with one flavor [11, 12] and will be relevant also for our analysis. Theories of this type theories emerge naturally in string theory via orientifold projections.

The salient feature, found in [10], is that the S-type theories are near conformal already at $N_{Tf} = 2$. This should be contrasted with theories with fermions in the fundamental representation for which the minimum number of flavors required to reach the conformal window is eight. In the following $S(N, N_{Tf})$ $(A(N, N_{Tf}))$ represents an S(A)-type theory with N colors and N_{Tf} Dirac fermions.

The $N = 3$ model with A-type fermions is just ordinary QCD with N_f flavors and the maximum allowed number of flavors is 16. For $N = 2$ the antisymmetric representation goes over to the pure Yang-Mills with a singlet fermion. For S-type models, asymptotic freedom is lost already for three flavors when $N = 2$ or 3, while the upper bound of $N_{Tf} = 5$ is reached for $N = 20$ and does not change when N is further increased. A small number of flavors is generic to the near conformal condition, which, as explained, is a favorable feature for models of electroweak symmetry breaking.

In the theory with S-types, we therefore know that the number of flavors must be smaller than 5 for the theory to yield chiral symmetry breaking. This takes into account that there is also a conformal window of size $N_{Tf}^c < N_{Tf} < 5$, with the critical value N_{Tf}^c to be determined shortly. In [10] it has been shown that a theory with two S-types is very close to the conformal window from $N = 2$ up to a quite large N.

FERMION MASSES AND FCNC PROBLEM

To generate fermion mass in technicolor models one needs additional interactions, arising from extended tech-

$G(N, N_{Tf}/2)$	$\mathbf{S}$	Higgs Mass	FCNC
$TC(2,1)$	$1/3\pi$	$\sim 1\,\mathrm{TeV}$	×
$S(2,1)$	$1/2\pi - \delta$	$\sim 200 - 500\,\mathrm{GeV}$	✓
$S(3,1)$	$1/\pi - \delta$	$\sim 200 - 500\,\mathrm{GeV}$	✓
$WTC(2,4)$	$4/3\pi - \delta$	?	✓
$S(4,1)$	$5/3\pi - \delta$	$\sim 200 - 500\,\mathrm{GeV}$	✓
$A(4,4)$	$4/\pi - \delta$	$\sim 200 - 500\,\mathrm{GeV}$	✓

TABLE II: Properties of models discussed in the paper. TC is ordinary technicolor, WTC walking technicolor, S models have symmetric two-index matter, and A models have antisymmetric two-index matter. N and N_{Tf} are colors and flavors.

nicolor (ETC), which couple technifermions to ordinary fermions [13]. However, the ETC interaction typically leads to unacceptably large flavor-changing neutral currents. This problem is less severe if the technifermion bilinear, whose condensate breaks electroweak symmetry, has a large anomalous dimension. This happens when the critical coupling for triggering condensation is slightly larger than (but close to) the infrared fixed point, $\alpha_c \geq \alpha_*$.[14]

For $SU(N)$ gauge theories, the critical coupling is given in the ladder approximation as $\alpha_c = \pi/(3C_2(R))$, where $C_2(R) = (N+2)(N-1)/N$ for the second rank symmetric tensors. Since the the coupling varies slowly up to a scale $\Lambda_* \simeq \Lambda_{\mathrm{TC}} \exp\left(\pi/\sqrt{\alpha_*/\alpha_c - 1}\right)$, which is larger than $300\Lambda_{\mathrm{TC}}$ for both $N = 2, N_{Tf} = 2$ and $N = 3, N_{Tf} = 2$, we take the anomalous dimension γ of the techni bilinear to be close to unity [15], and

$$\langle \widetilde{q}\, q \rangle_{\mathrm{ETC}} \simeq \left(\frac{\Lambda_{\mathrm{ETC}}}{\Lambda_{\mathrm{TC}}}\right) \langle \widetilde{q}q \rangle_{\mathrm{TC}}. \tag{1}$$

The enhancement of the condensate allows reasonable masses for light quarks and leptons, even for large ETC scales necessary to sufficiently suppress flavor-changing neutral currents. However, to obtain the observed top mass, we must rely on additional dynamics, as in so-called non-commuting ETC models, where the ETC interaction does not commute with the electroweak interaction [16].

If our goal is only to obtain an effective theory valid up to the scale $\Lambda_{\mathrm{ETC}} \sim 10^3$ TeV, we need not explain the origin of ETC operators (this is in the spirit of so-called "little-Higgs" models [17]). We leave an explanation of quark and lepton masses for future work.

SMALL S PARAMETER

The models considered here produce smaller values of $\mathbf{S}$ than traditional technicolor models, because of the smaller particle content and because of the near-conformal dynamics. The effect of smaller number of particles can already be seen in Table 2, column $\mathbf{S}$. The first

number given in each entry is the perturbative estimate, which is just $1/6\pi$ for each new electroweak doublet. For S-type models the result is

$$\mathbf{S}_{\text{pert.}}(S) = \frac{1}{6\pi} \cdot \frac{N(N+1)}{2} \cdot \frac{N_{Tf}}{2} \ , \qquad (2)$$

while for A-type models it is

$$\mathbf{S}_{\text{pert.}}(A) = \frac{1}{6\pi} \cdot \frac{N(N-1)}{2} \cdot \frac{N_{Tf}}{2} \ . \qquad (3)$$

However, near-conformal dynamics leads to a further reduction in the $\mathbf{S}$ parameter [6, 7]. In the estimate of [6], based on the operator product expansion, the factor of $\frac{1}{6\pi}$ in the above equations is reduced to about .04, which is a thirty percent reduction. For example, the best estimate for $\mathbf{S}$ in the S(3,1) model is about .2, which is within the 68% confidence ellipse in the $\mathbf{S}$-$\mathbf{T}$ plane [1].

LIGHT HIGGS FROM HIGHER REPRESENTATIONS

In the analysis of QCD-like technicolor models one simply scales up QCD phenomenology to obtain predictions at the electroweak scale. The Higgs particle can then be mapped to the scalar chiral partner of the Goldstone bosons which are eaten by the W and Z gauge bosons. Naive scaling estimates yield a very heavy composite Higgs with mass of the order a TeV: $m_H \sim 4\pi F_\pi$, with F_π the electroweak scale.

There is, however, no guarantee that such estimates can be trusted in WTC or near-conformal models. One cannot simply scale up QCD to obtain useful nonperturbative information. In order to estimate the Higgs mass we will use the observation made recently in [11] that *non-supersymmetric* Yang-Mills theories with a Dirac fermion either in the two index symmetric or antisymmetric representation of the gauge group are nonperturbatively equivalent to supersymmetric Yang-Mills (SYM) theory at large N, so that exact results established in SYM theory should hold also in these "orientifold" theories. The orientifold theories at finite N were studied in [12], and many of the discovered properties, such as almost parity doubling and small vacuum energy density, are appealing properties for dynamical breaking of the electroweak theory [7]. We emphasize again that supersymmetry is only used as a tool here to extract non-perturbative information about our models, which are not themselves supersymmetric.

To estimate the Higgs mass for fermions in the S-type representation of the gauge group we use the large N limit while setting $N_{Tf} = 1$ (since in our case of interest $N_{Tf} = 2$ the results are approximate, but probably roughly accurate). The Higgs particle is then identified with the scalar fermion-antifermion state whose pseudoscalar partner in ordinary QCD is the η'. At large

N this theory is mapped into super Yang-Mills using [11]. The low lying bosonic sector contains precisely a scalar and a pseudoscalar meson. Due to the supersymmetry correspondence the latter are expected to become degenerate at infinite N. In the supersymmetric limit we can relate the masses to the fermion condensate $\langle \widetilde{q}q \rangle \equiv \langle \widetilde{q}^{\{i,j\}} q_{\{i,j\}} \rangle$ [12]:

$$M = \frac{2\,\alpha}{3} \left[\frac{3\,\langle\widetilde{q}q\rangle}{32\pi^2\,N} \right]^{\frac{1}{3}} = \frac{2\hat{\alpha}}{3}\Lambda \ , \qquad (4)$$

with $\langle\widetilde{q}q\rangle = 3N\Lambda^3$ and Λ the one loop, large N, invariant scale of the theory:

$$\Lambda^3 = \mu^3 \left(\frac{16\pi^2}{3Ng^2(\mu)} \right) \exp \left[\frac{-8\pi^2}{Ng^2(\mu^2)} \right] \ . \qquad (5)$$

We have also defined:

$$\hat{\alpha} = \alpha \left[\frac{9}{32\pi^2} \right]^{\frac{1}{3}} \ . \qquad (6)$$

The unknown numerical parameter $\hat{\alpha}$ is expected to be of order one and is the coefficient of the Kähler term in the Veneziano-Yankielowicz effective Lagrangian describing the lowest composite chiral superfield. Taking for example $\hat{\alpha} \sim 1 - 3$ (see the discussion below) one would roughly deduce, at large N and for $N_{Tf} = 1$, a Higgs mass in the range:

$$m_H = M \simeq 200 - 500 \text{ GeV} \ . \qquad (7)$$

Here we have chosen $\Lambda = \Lambda_{TC} \sim 250$ GeV [19]. We expect $1/N$ corrections. Fortunately these corrections were estimated, for $N_f = 1$, in [12] and differ for theories of type S and A. For the S-type models we have:

$$\frac{m_H(S)}{M} = 1 - \frac{4}{9N} + \frac{1}{8N} \frac{\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle}{\hat{\alpha}\,\Lambda^4} + O(N^{-2}) \ , \quad (8)$$

where $\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle$ is the technigluon condensate. Since $\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle \sim \Lambda^4$ and $\hat{\alpha}$ is order one the second term dominates and further reduces the Higgs mass with respect to the large N limit. This should be compared to the $1/N$ corrections for the A-type theory:

$$\frac{m_H(A)}{M} = 1 + \frac{4}{9N} + \frac{1}{8N} \frac{\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle}{\hat{\alpha}\,\Lambda^4} + O(N^{-2}) \ , \quad (9)$$

which indicate that the Higgs becomes heavier as we reduce the number of colors. Since for $N = 3$ the fermions, for type A theories, are in the fundamental representation, our results are qualitatively in agreement with the standard expectations that the Higgs for theories with technifermions in the fundamental representation is expected to be heavy.

To reassure ourselves that $\hat{\alpha}$ is, indeed, an order one quantity we recall that the A-type theory with one flavor is mapped into super Yang-Mills at large N. But,

for $N = 3$ the A-type theory is QCD with one flavor, since the fundamental and two-index antisymmetric representations are the same in $SU(3)$. This observation was made long ago by Corrigan and Ramond [18]. The η' state is the pseudoscalar partner of the scalar fermion-antifermion state (i.e. the Higgs) and its mass for one flavor can be simply estimated as follows:

$$m_{\eta'}^2(N_f = 1) = \frac{N_f}{3} m_{\eta'}^2 \; , \qquad (10)$$

where we used Witten and Veneziano's standard large N and finite N_f scaling, with $N = 3$. Comparing this mass with the supersymmetric limit by identifying M with $m_{\eta'}$ we estimate:

$$\hat{\alpha} \sim \frac{\sqrt{3}}{2} \frac{m_{\eta'}}{\Lambda} \sim 3.2 \frac{\sqrt{3}}{2} \sim 2.8 \; . \qquad (11)$$

Here $m_{\eta'} = 958$ MeV is the ordinary 3-flavor QCD mass for the η' and $\Lambda \sim 300$ MeV is identified with the characteristic QCD invariant scale. It is encouraging that we obtained the suggested order one result used earlier. Lattice simulations should be able to improve the estimate for the Higgs mass in our models.

Somewhat surprisingly we find a light scalar, presumably narrow. Our calculations suggest that the favored S-type models naturally produce light composite Higgs bosons.

CONCLUSIONS

In this letter we investigate a new class of models of dynamical electroweak symmetry breaking with technifermions in higher representations. These models lie close to the conformal window, and are free from the flavor-changing neutral current problem despite small numbers of flavors and colors. Their contribution to the **S** parameter is small and not excluded by precision data. Due to the large N equilvalence of our models to supersymmetric Yang-Mills theory, we can make quantitative estimates of the mass of the Higgs. It turns out to be surprisingly light (and perhaps narrow): $m_H \sim 200 - 500$ GeV.

The phenomenology of our models is quite distinct from QCD-like models for two reasons: the near-conformal behavior alters the dynamics, and the two-index matter representations imply that color singlet interpolating operators for bound states are very different from QCD.

Acknowledgements

* Electronic address: dkhong@pusan.ac.kr
† Electronic address: hsu@duende.uoregon.edu
‡ Electronic address: francesco.sannino@nbi.dk

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